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Shear Strength in the Zone of Freezing in Saline Soils

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Abstract

Laboratory direct shear strength tests were conducted on sand and clay soil samples as they were freezing. Samples prepared with seawater and distilled water were tested in a modified direct shear box at shear plane temperatures ranging from 0°C to -5°C.

The shear strengths of the freezing saline clay and sand samples were observed to be significantly less than shear strengths of the fresh water samples.

For the clay samples, these shear strength differences could be accounted for principally by the 1.8°C freezing point depression caused by the salts in the sea water, the two shear strength curves nearly paralleling and overlapping each other when plotted versus temperature below freezing. In a similar plot for the sands, the two curves diverge considerably from a common strength at 0°C.

It is shown that the shear strength reduction of the saline clay soil is principally the result of increased unfrozen water content. It is postulated that knowledge of unfrozen water content relationships for frozen saline soils will probably allow better predictive capabilities for the shear strength in the freezing zone.

Introduction

The design of artificial islands and other geotechnical structures to support offshore petroleum resource development and production in the Beaufort Sea will require considerable knowledge of the strength of frozen saline soils. This information will be particularly important if the design is predicated on the development of ice bonding to develop the shear strength necessary to resist the forces of sea ice. In particular, knowledge of the shear strength of saline soils in and near the zone of freezing will be important as this region may define a potential failure plane. However, little is known about the shear strength of freezing saline soils. Most studies of the strength of frozen saline soils have concentrated on the compressive strength and have not examined shear strength nor been directed toward the critical zone of freezing.

The unique character of the freezing zone is that it is a dynamic region of heat and mass flow. It is also characterized by large amounts of unfrozen water because of the relatively high temperatures.

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Table 1. Properties of test materials.

Material (1)	Percent finer than 2.0 mm (2)	0.42 mm (3)	0.074 mm (4)	0.02 mm (5)	0.005 mm (6)	0.001 mm (7)	Liquid limit in percent (8)	Plasticity index, in percent (9)	Uniformity coefficient (10)	Unified soil classification (11)
Clay	100	100	99	84	52	26	30	9	16	CL
Sand	96	68	40	18	6	1	25	NP	29	SM

Note: 25.4 mm = 1 inch.

In soils containing freshwater pore fluids, this zone can have considerable thickness (1), with fingers of ice projecting out from the top of the zone where ice lenses are forming to the bottom of the freezing zone where ice growth begins. In saline soils, the freezing zone is even more complicated, with soluble salts concentrating in unfrozen water films and brine pockets, and ice lens growth occurring at many sites simultaneously.

If temperature gradients are very low (small temperature changes with increasing depth), as they may be in artificial islands in deep seawater, the zone of freezing may be very thick, extending over many meters of depth.

Because of the planar nature of the freezing zone, the only practical method of determining its strength is the direct shear test, which forces shearing to occur in a preselected plane. This study reports on a set of laboratory direct shear tests conducted on freezing sand and clay soils with seawater and distilled water pore fluids.

Material Description

Two frost-susceptible soils, a fine-grained sand and a clay, were selected for this study. The choice of materials was dictated by the desire to study plastic and non-plastic soils and by the size and shear stress capacity limitations of the available direct shear apparatus. The sand is a well-graded granular material containing numerous fines. The clay is a much finer grained material with a low plasticity. The properties of each of these materials are given in Table 1.

Direct Shear Apparatus

A standard direct shear (single shear) apparatus was modified to study the shear strength in the freezing zone. The apparatus consists of a circular phenolic shear box driven by a variable speed motor. The load is applied through a miniature load cell mounted on a linear ball - bushing - guided load shaft. The horizontal and vertical deformations are monitored by direct current displacement transformers (DCDTs), and are continuously recorded on a strip chart recorder. The shear box (Fig. 1) accommodates a test sample 50 mm (2 in.) in diameter and 58 mm (2.3 in.) in height. It is made up of four inner rings which contain the test sample and two outer rings through which the shear load is transferred. The inner rings are lined with a thin rubber membrane. This arrangement allows the sample to be frozen with little side friction restraining frost heave. The rubber membrane also prevents water leakage and, thus, allows the water table to be level with the top of the sample during freezing.

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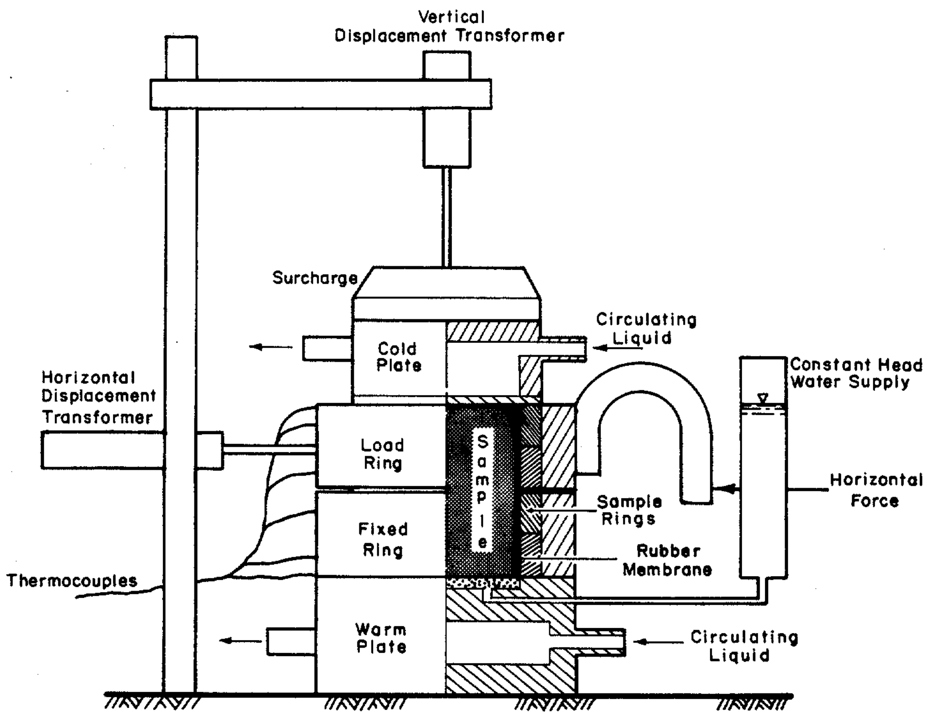


Figure 1. Schematic of shear box.

Water is available under a constant head through a porous bronze plate set in the base of the shear box. The base also contains a heat exchange chamber through which an ethylene glycol solution is circulated from a refrigerated bath. A second heat exchange plate is positioned on top of the sample. It is connected to a another refrigerated bath so that the top and bottom boundary temperatures can be controlled independently. The sample is frozen by adjusting the temperatures of the circulating baths to obtain the desired temperature gradient, and then programming the bath temperatures to decrease to achieve the desired frost penetration rate. Radial heat flow is minimized by insulating the shear box and maintaining the ambient room temperature 1°C (2°F) above the desired shear plane temperature.

The vertical load on the shear plane is applied through a balance, hanger and weight system common to older types of direct shear devices.

Sample Preparation

The samples were compacted in the direct shear device using a Harvard miniature compaction hammer. Replicate specimens were prepared using both distilled water and seawater as pore fluids. Prior to saturation, calibrated thermocouples were inserted through the rubber membrane into the sample and sealed with a liquid rubber compound. The samples were then saturated by gradually raising the head of the water supply to a position level with the top of the sample. The degree of saturation with this method was better than 95%.

Test Procedure

The samples were sheared at shear plane temperatures ranging between 0 and -5°C (32 and 23°F) with a temperature gradient in the shear zone of approximately 0.02°C/mm (0.9°F/in.). The test temperatures were selected to allow the determination of the shear strength over a range of temperatures, with an emphasis put on temperatures close to the freezing point of the pore water solution. The shear stress capacity of the apparatus (1200 kPa or 175 psi) limited the selection of the lowest test temperature.

Once the desired shear plane temperature was reached, the sample was sheared at a rate of approximately 0.03 mm/sec (4.7 in./hr.). Peak stresses usually developed within 4 mm (0.16 in.) of horizontal deformation. For the tests with the highest shear plane temperatures, the peak stresses were not so well defined. In these cases the peak stress was selected as the stress at 4 mm horizontal deformation.

Upon completion of the direct shear tests, each sample was cut into six horizontal slices to determine the water content, salinity and density profiles. The salinities were determined by suspending the oven-dry material remaining after the water content determination in a known quantity of distilled water, and determining the electrical conductivity of the solution 24 hours after the mineral solids settled out. The conductivity for the original water content was then back-calculated and the salinity and freezing point calculated using established relationships for seawater.

Test Results

A total of 33 direct shear tests were conducted, 19 on the clay and 14 on the sand. A normal stress of 60 kPa (8.7 psi) was imposed in most of the tests. A normal stress of 15 kPa (2.2 psi) was employed for 6 of the tests on the clay to identify the surcharge effect.

Examples of the resulting shear stress versus deformation curves are illustrated in Figure 2. It can be seen that at lower temperatures the peak stresses are well defined, whereas at temperatures close to the freezing point, ≃ -1.8°C (28.8°F) for seawater, the curves rise gradually, with no apparent maximum values.

Table 2 contains a summary of the sample properties, the test conditions and the observed failure stresses. The sample properties are for a zone approximately 10 mm (0.4 in.) wide encompassing the shear plane. The table shows that the shear strength increases with decreasing temperature for both soils

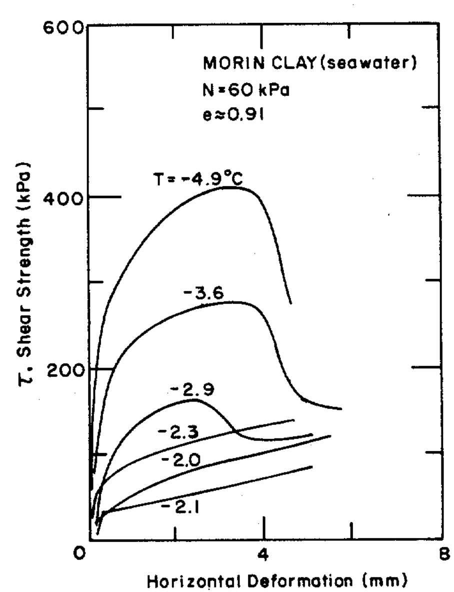


Figure 2. Example of shear stress-deformation curves.

Table 2. Sample properties and test results.

Void ratio e (1)	Water content w, in percent (2)	Pore water salinity, S in parts per thousand (3)	Normal stress N, in kilopascals (4)	Shear plane temperature T_{sp}, in °C (5)	Shear plane freezing point FP_{sp}, in °C (6)	Tempeature below freezing ΔT_{sp}, in °C (7)	Maximum shear strength τ_{sp}, in kilopascals (8)
CLAY - SEAWATER PORE FLUID							
0.80	26.4	43.2	15	-2.2	-1.8	-0.4	104
0.92	33.4	37.5	15	-1.6	-2.0	-0.4	57*
0.94	34.1	39.2	15	-2.1	-2.1	0.0	89*
0.97	32.1	42.5	15	-3.7	-2.2	-1.5	239
0.84	30.3	42.0	15	-2.0	-2.2	0.2	71*
0.81	29.2	39.2	15	0.0	-2.1	2.1	18*
0.94	31.3	35.3	60	-2.0	-1.9	-0.1	102*
0.94	31.2	38.8	60	-2.3	-2.1	-0.2	134*
1.01	33.4	37.3	60	-3.6	-2.0	-1.6	277
0.80	29.0	43.3	60	-2.1	-2.4	0.3	73*
0.93	30.9	40.1	60	-2.9	-2.1	-0.8	166
0.99	32.8	37.2	60	-4.9	-2.0	-2.9	411
0.77	27.9	34.5	60	-1.4	-1.8	0.4	83*
CLAY - DISTILLED WATER PORE FLUID							
0.70	25.3	1.2	60	0.0	-0.1	0.1	51*
1.02	33.9	0.7	60	-0.3	0.0	-0.3	130*
1.00	33.3	0.6	60	-2.9	0.0	-2.9	458
1.00	33.3	0.9	60	-1.9	0.0	-1.9	338
0.80	29.0	0.4	60	0.0	0.0	0.0	32*
0.87	28.9	0.6	60	-0.2	0.0	-0.2	60*
0.86	28.6	0.5	60	-0.2	0.0	-0.2	67*
SAND - SEAWATER PORE FLUID							
0.63	21.6	27.0	60	-1.6	-1.4	-0.2	88
0.58	21.6	29.5	60	-1.5	-1.5	0.0	98
0.62	21.0	29.3	60	-2.3	-1.5	-0.8	238
0.59	20.0	31.0	60	-1.4	-1.6	0.2	114*
0.70	23.7	35.5	60	-1.9	-1.9	0.0	139
0.68	23.2	32.4	60	-4.3	-1.8	-2.5	403
0.59	21.8	30.0	60	-1.0	-1.6	0.5	107*
0.68	23.0	35.0	60	-3.9	-1.8	-2.1	306
SAND - DISTILLED WATER PORE FLUID							
0.54	18.4	3.4	60	0.0	-0.2	-0.2	25*
0.52	19.5	14.8	60	-0.9	-0.8	0.1	28*
0.66	22.4	2.6	60	-0.7	-0.1	-0.6	408
0.62	22.9	3.6	60	-0.1	-0.2	0.1	60*
0.72	24.3	1.6	60	-0.5	-0.1	-0.5	393
0.75	25.5	2.1	60	-0.3	-0.1	-0.2	96
0.73	24.8	1.6	60	-0.5	-0.1	-0.4	276

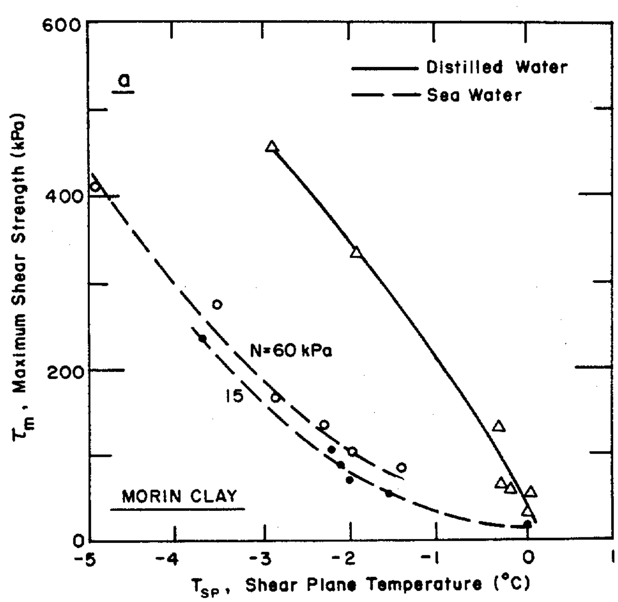
Notes: * Shear strength at 4 mm (0.16 in.) horizontal deformation.
1 kPa = 0.145 psi
Deg. C = (Deg. F - 32) 5/9

and that samples in the series with saline pore water are much weaker than those in the series with distilled pore water. The water contents and the void ratios within each series are similar. There is, however, a slight tendency for the water content and void ratio to increase with decreasing shear plane temperature. This indicates that the shear plane was in a zone where ice segregation and frost heave had occurred.

Discussion of Results

The dependence of the shear strength τ_{sp} in and near the freezing zone on the shear plane temperature T_{sp} is clearly illustrated in Figure 3a for the clay and in Figure 3b for the sand. The curves shown were obtained by fitting second degree polynomial curves to the data using multiple linear regression and analysis of variance techniques. As the variation in void ratio was small for each of the soils, no relationship of τ_{sp} to void ratio passed an F-test with an uncertainty of 0.05 or less. The relationships between τ_{sp} and T_{sp}, however, were strong in all cases, as was the contribution of normal stress N in the case of the clay with seawater pore fluid. The relationships between τ_{sp} and T_{sp} were linear for both the seawater and distilled water series for the sand. For the clay these relationships are non-linear at temperatures near the freezing points of the pore fluids, but become more linear as test temperatures decrease. For the clay, the effect of seawater appears to be primarily to shift the τ_{sp} and T_{sp} curve along the temperature axis an amount approximately equal to the freezing point depression of seawater. For the sand, this is not the case as the seawater and distilled water curves diverge strongly.

Indeed, if the shear strengths are plotted versus the difference ΔT_{sp} between the shear plane temperature and the freezing point of the seawater (Figs. 4a and 4b), it can be seen that the shift of the freezing point almost totally accounts for the differences in shear



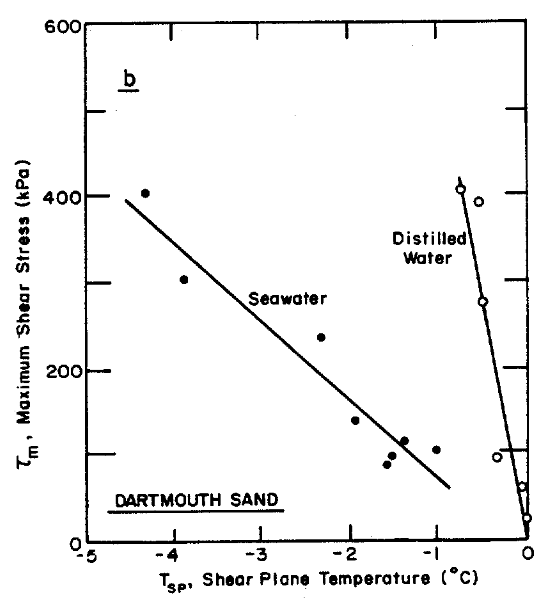


Figure 3. Dependence of maximum shear stress on shear plane temperature: (a) clay; (b) sand.

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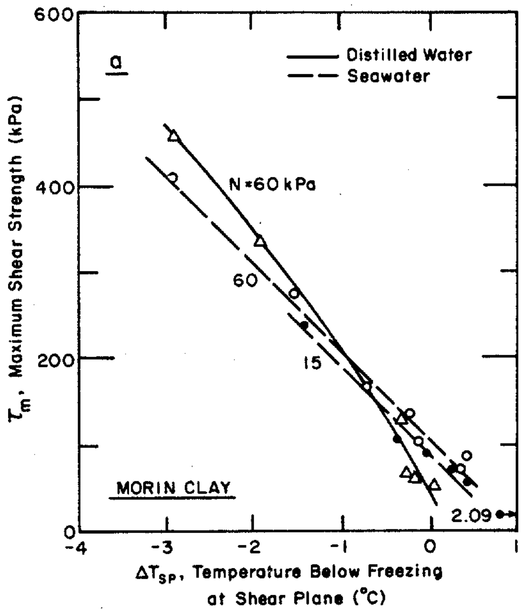

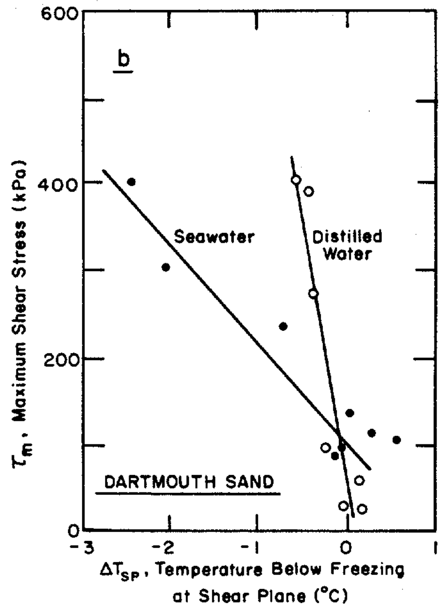

Figure 4. Maxmimum shear stress versus temperature of pore fluid below freezing: (a) clay; (b) sand.

strength between the distilled water and seawater series for the clay, but not for the sand.

Ogata et al. (2) found that the effect of salinity on the unconfined compressive strength of frozen sands, silts, and clays can be accounted for by unfrozen water content data. This results because the soluble salts in seawater cause an increase in the unfrozen water content.

Similar results were found for the clay test material (Fig. 5), the shear strength decreasing with increasing unfrozen water content. Because the laboratory unfrozen water content tests were incomplete as of the writing of this report, the unfrozen water content data are estimates. The unfrozen water content data for the distilled water-clay series were obtained from previously published results of Tice et al. (3) for the same clay soil but from a different batch. For the seawater-clay series, the unfrozen water contents were estimated using a predictive method suggested by Tice et al. (4) based on the electrical conductivity of the soil water. Figure 5 shows that data points for both the distilled water and seawater cases are located within the same scatter band. It, thus, can be seen that the unfrozen water content is a satisfactory predictor of shear strength of the clay soil in and near the freezing zone. A more thorough examination of the relationship of the shear strength in the freezing zone to unfrozen water content will be made when the unfrozen water content data for the two test soils become available.

As previously discussed, the unfrozen water in freezing and frozen saline soils occurs in two different locations. This is an important topic because the unfrozen water adjacent to soil particles reduces the

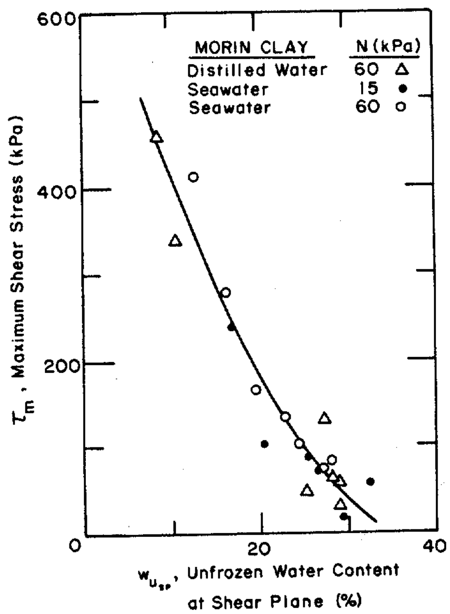

Figure 5. Maximum shear stress versus estimated unfrozen water content for the clay.

strength of the ice-soil particle bond; whereas, the unfrozen water in brine pockets reduces the strength of the ice component.

For a group of frozen cohesive soils, Ogata et al. (2) found that the compressive strength could be related to the thickness of the unfrozen water films. This result suggests that for fine grained soils that the unfrozen water films control the strength. However, in coarser grained soils such as sands and gravels, the brine concentration within the ice component will have a significant impact on the strength. Moreover, it seems reasonable that there is a transition from strength of the ice-soil bond to the strength of the ice component dominating the strength of the ice-water-soil mass as the particle size increases. While this information may not be necessary to determine the shear strength of freezing saline soils, it will be useful to develop a better understanding of the mechanisms involved. It is a subject for additional study.

Conclusions

The shear strength development in the freezing zone of a sand and a clay is greatly affected by the soluble salts in seawater, particularly in the case of the sand. The shear strength reduction in the clay but not in the sand can be accounted for by the freezing temperature shift due to the soluble salts in seawater. For both the clay and the sand, dependence of shear strength on the unfrozen water content will probably result in better predictive capabilities for the shear strength in and near the freezing zone.

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REFERENCES

1. Miller, R.D., "Frost Heaving in Non-Colloidal Soils," in Proceedings of the Third International Conference on Permafrost, National Research Council of Canada, vol. 1, pp. 708-713.

2. Ogata, N., Yasuda, M., and Kataoka, T., "Salt Concentration Effects on Strength of Frozen Soils," in Proceedings of the Third International Symposium on Ground Freezing, USA Cold Regions Research and Engineering Laboratory, Special Report 82-16, pp. 3-10.

3. Tice, A.R., Burrows, C.M., and Anderson, D.M., "Determination of Unfrozen Water in Frozen Soil by Pulsed Nuclear Magnetic Resonance," in Proceedings of the Third International Conference on Permafrost, National Research Council of Canada, vol. 1, pp. 150-155.

4. Tice, A.R., Zhu Y., and Oliphant, J.L., "The Effects of Soluble Salts on the Unfrozen Water Contents of the Lanzhou, P.R.C., Silt," USA Cold Regions Research and Engineering Laboratory, CRREL Report 84-16, 18 p.